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Dissipation kinetics and risk assessment of chlorantraniliprole and lambda-cyhalothrin in okra (*Abelmoschus esculentus*) and soil

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ABSTRACT

A field experiment was conducted to elucidate the dissipation kinetics, persistence, and risk assessment of chlorantraniliprole and lambda-cyhalothrin applied as ready-mix insecticide in okra [*Abelmoschus esculentus* (L.) Moench] and associated soil in April 2023 at Chaudhary Charan Singh Haryana Agricultural University, Hisar, Haryana. A mix formulation of chlorantraniliprole (9.3%) + lambda-cyhalothrin (4.6%) was applied at the fruiting stage of okra (Hisar 102 variety) in different doses (28, 35 and 56 g a.i./ha). The samples were analysed using a validated QuEChERS extraction protocol followed by GC-MS/MS quantification. Both insecticides confirmed to first-order dissipation kinetics, with half-lives of 1.40–4.36 days in okra fruits. Residues declined below the MRL within six days after application, establishing safe pre-harvest intervals. Dietary and soil risk assessments, based on estimated daily intake and risk quotient indicated negligible human and ecological risk. These findings provide critical data for residue management, regulatory compliance, and suitability of chlorantraniliprole and lambda-cyhalothrin in okra cultivation.

Keywords: Dietry risk assessment, Environment, QuEChERS, Residue dynamics

Okra [*Abelmoschus esculentus* (L.) Moench], despite its adaptability and popularity as a rich source of vitamins, minerals, and dietary fibre, is highly susceptible to insect-pest infestation throughout its growth stages (Mohapatra *et al.* 2024, Ounis *et al.* 2024). The crop is frequently attacked by fruit and shoot borer (*Earias vitella* Fab.), whiteflies (*Bemisia tabaci* Genn.), jassids (*Amrasca biguttula biguttula* Ishida), aphids (*Aphis gossypii* Glover), and red cotton bug (*Dysdercus suturellus* Herrich-Schaeffer) (Kodandaram *et al.* 2017, Prasad *et al.* 2025). These pests can cause significant damage by feeding on tender shoots, flowers, leaves, and developing fruits. Among the commonly used insecticides, chlorantraniliprole and lambda-cyhalothrin are frequently used for effective control of okra pests.

Chlorantraniliprole (CAP) is an anthranilic diamide insecticide that acts by binding to the ryanodine receptors in insects. This disrupts normal calcium release, leading to rapid muscle dysfunction, paralysis and ultimately death (Wang *et al.* 2025). It is generally applied as a foliar spray and provides long-lasting control against a wide range of insect-pests, particularly lepidopteran and dipteran species (Nakajima *et al.* 2018, Barmota *et al.* 2023, Lin *et al.* 2024). Lambda-cyhalothrin (LC) is a synthetic pyrethroid which targets voltage-gated sodium channels, in addition to affecting calcium and chloride ion channels, which results in hyperexcitation, loss of coordination, and eventual death of the target insect (Seenivasan and Muraleedharan 2009, Choi *et al.* 2024). While these insecticides ensure effective pest control, their residues in okra fruits and soil may threaten consumer health and non-target organisms. Persistent exposure can cause chronic toxicity and environmental contamination. Hence, the experiment was conducted to study the residue dynamics and field dissipation of chlorantraniliprole and lambda-cyhalothrin in okra for safe application and accurate pre-harvest interval determination.

MATERIALS AND METHODS

Field experiment: The field experiment was conducted in April 2023 at Chaudhary Charan Singh Haryana Agricultural University, Hisar (29°8´N, 75°42´E; at an elevation of 211.3 m amsl), Haryana. The experiment was laid out in a randomised block design (RBD). A ready-mix formulation of chlorantraniliprole (9.3%) + lambda-cyhalothrin (4.6%) was applied at the fruiting stage of okra (variety Hisar 102) @28 g a.i./ ha (standard dose), 35 g a.i./ ha (1.25 times standard dose), and 56 g a.i./ ha (double dose). The insecticide was applied as a single foliar spray using a knapsack sprayer

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calibrated to deliver uniform spray volume. Sampling was carried out at predefined intervals of 0 (2 h after spray), 1, 3, 5, 7, 10, and 15 days after application (DAA) to study the dissipation pattern. At each sampling interval, approximately 1 kg of okra fruits from different plants and 1 kg of soil from beneath the crop (0–15 cm depth) were collected from each treated plot (5 m × 5 m) after spraying, while an untreated plot served as control. All samples were placed in clean zip lock polythene bags, properly labeled, and brought to the laboratory for dissipation studies.

Instrument (GC-MS/MS) and parameters: The chromatographic separation of insecticides was attained by Schimadzu gas chromatography tandem mass spectrometry (GC-MS/MS-8040) system equipped with SH-Rxi-5Sil MS (length-30 m, 0.25 mm and thickness-0.25 μm) column. The injection volume was 1 μL, with the injector maintained at 250°C and the detector at 300°C. The carrier gas was operated in linear flow mode at 44.5 cm/s. The insecticides were analysed using multiple reaction monitoring (MRM) mode on GC-MS/MS. CAP showed a retention time of 20.04 min, while LC exhibited retention times of 21.35 and 21.61 min (Fig. 1). Further confirmation was achieved using their precursor and product ions in ESI^+ mode. For CAP, the precursor ion $[M+H]^+$ was 484.0, with quantifier and qualifier ions of 452.89 and 285.76, respectively. In the case of LC, the precursor ion $[M+H]^+$ was 489.0, and the quantifier and qualifier ions of 197.12 and 181.54, respectively.

Method validation and food processing: The method validation and associated analytical parameters for this experiment were conducted as per the procedure by Khokhar *et al.* (2025). In addition to our earlier study, accuracy was further assessed through reproducibility (inter-day assay) by spiking insecticide mixture standards at seven levels (1, 0.5, 0.25, 0.1, 0.05, 0.025, and 0.01 mg/kg). The limit of detection (LOD) and limit of quantification (LOQ) for CAP and LC in okra fruits and soil were found to be 0.005 mg/kg and 0.01 mg/kg, respectively. Extraction of insecticide residues from okra fruits and soil was carried out using a modified QuEChERS method as described by Anastassiades *et al.* (2003).

Residue dynamics: The dissipation kinetics of CAP and LC were evaluated by fitting the residue data in different kinetic models, viz. zero-order, first-order, and second-order equations. The goodness of fit was assessed by comparing the coefficients of determination (R^2), and the model yielding the highest R^2 value was considered the best fit. The pre-harvest interval (PHI) was determined as (Srinivas *et al.* 2012):

$$\mathrm{PHI} = \frac{\ln (C_0/\mathrm{MRL})}{k} \quad (1)$$

Where C_0, Initial residue; MRL, Maximum residue limit; k, Dissipation rate constant.

Risk evaluation: The potential risk to human and soil health posed by CAP and LC residues in the okra ecosystem was assessed by calculating the risk quotient (RQ). This calculation was performed using formula (2) (Mukherjee *et al.* 2021):

$$RQ_d = \frac{\text{Estimated daily intake}}{\text{Acceptable daily intake} \times \text{Body weight}} \quad (2)$$

The Acceptable Daily Intake (ADI) for CAP and LC in humans is 1.56 mg/kg body weight (Biswas *et al.* 2024) and 0.0025 mg/kg body weight (EFSA 2020), respectively. Estimated Daily Intake (EDI) is evaluated using formula (3) in mg/kg body weight.

$$\mathrm{EDI} = \text{Pesticide residue} \times \text{Food intake} \quad (3)$$

According to Mariappan and Kaithamalai (2020), the average daily vegetable consumption in India is 200 g/person, while the maximum daily intake of okra for a 55 kg individual is 9.4 g. Bhandari *et al.* (2021) described the risk quotient for soil biota which can be determined through formula (4).

$$RQ_s = \frac{\mathrm{MSC}}{\mathrm{PNEC}} \quad (4)$$

Where MSC, Measured pesticide concentration in soil (mg/kg); PNEC, Predicted no-effect concentration for acute toxicity.

RESULTS AND DISCUSSION

Method validation: The between-batch variability for fortified okra samples were processed using QuEChERS method over three consecutive days (reproducibility). For CAP, the percent recoveries ranged from 88.2–90.3% across the specified spiking levels, with relative standard deviations of reproducibility (RSD_R) from 0.89–1.31%. LC's percent recoveries ranged from 88.3–90.9%, with RSD_R from 0.88–1.51%. All the observed percent recoveries and relative standard deviations were adequate according to European Commission guidelines (2021) which

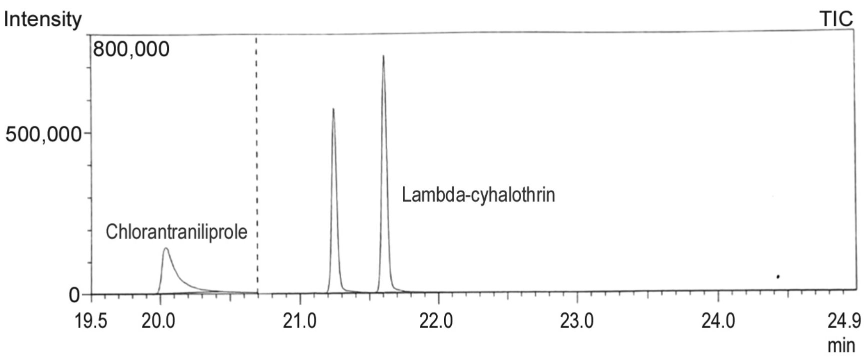

Fig. 1 Chromatogram of chlorantraniliprole and lambda-cyhalothrin through GC-MS/MS.

states that a multi-residue method's recovery capability should be between 70 and 120%, with an RSD of under 20%. Therefore, the method was further validated through reproducibility (inter-day assay) accuracy.

Residue dynamics: For CAP, the initial residues were 0.079, 0.086, and 0.208 mg/kg at SD (single dose), 1.25 SD, and DD (double dose), respectively. These residues persisted up to 5 days with percent dissipation 86.08 and 84.88 for SD and 1.25 SD, respectively, and upto day 7 with percent dissipation 93.27 for DD (Table 1). After that, it reached below LOQ on day 7 for SD and 1.25 SD, and on day 10 for DD. In case of LC, the initial residues were 0.039, 0.055, and 0.158 mg/kg at SD, 1.25 SD, and DD, respectively. These residues persisted up to day 5 with percent dissipation 74.35 and 80.02 for SD and 1.25 SD, respectively, and on day 7 with percent dissipation 91.14 for DD (Table 2). After that, it reached below LOQ on day 7 for SD and 1.25 SD, and on day 10 for DD.

The dissipation data of CAP and LC was fitted in zero, first and second order as shown in Fig. 2 and 3, respectively. Both CAP and LC followed first-order kinetics at all the three doses with maximum coefficient of determination (R^2). The half-lives for SD, 1.25SD, and DD were 1.40, 1.97, and 3.09 days, respectively in case of CAP. For LC, the half-lives for SD, 1.25 SD, and DD were 3.36, 3.43, and 4.36 days, respectively. The findings of the present study are consistent with those reported by Mawtham *et al.* (2023), who demonstrated that CAP residues in bitter gourd at two doses dissipated following first-order kinetics, with approximately 99% dissipation observed in 15 days for X dose and 2X dose in 20 days after the application of CAP 18.5% SC, and reported half-lives of 2.44 and 2.79 days, respectively. Li *et al.* (2023) reported that CAP 20% SC dissipated according to first order kinetics in strawberries, having initial residue deposits of 0.072 mg/kg with a half-life of 11.7 days. Also, Singh *et al.* (2025) confirmed that chlorantraniliprole dissipates rapidly in okra fruits and soil, with residues falling below the LOQ within 7–10 days in fruits and 3–5 days in soil. The short half-life values indicated low persistence under field conditions. Initial residues were well below the EU MRL, even at double the recommended dose, suggesting minimal consumer risk. Bhattacherjee *et al.* (2021) reported that LC in mango at two doses i.e. single dose and double dose dissipated with a half-life of three days. Tong *et al.* (2021) examined the LC 2.5% EC on soyabean in China, and noted that half-lives for LC residues varied from 2.45–7.26 days, thereby following first order dissipation kinetics. The dissipation pattern observed in the present study aligns with Basnshtu *et al.* (2025) who reported first-order kinetics and short half-lives (1.11–1.68 days) of chlorantraniliprole + lambda-cyhalothrin formulation in chilli. However, comparatively higher half-life values of lambda-cyhalothrin in okra (3.36–4.36 days) observed in this study might be attributed to crop morphology and environmental variability. For CAP, the EDI values ranged from 0.0001–0.0019 mg/kg body weight/day, while for LC, the values ranged from 0.0001–0.0014 mg/kg body weight/day across different treatments and sampling intervals,

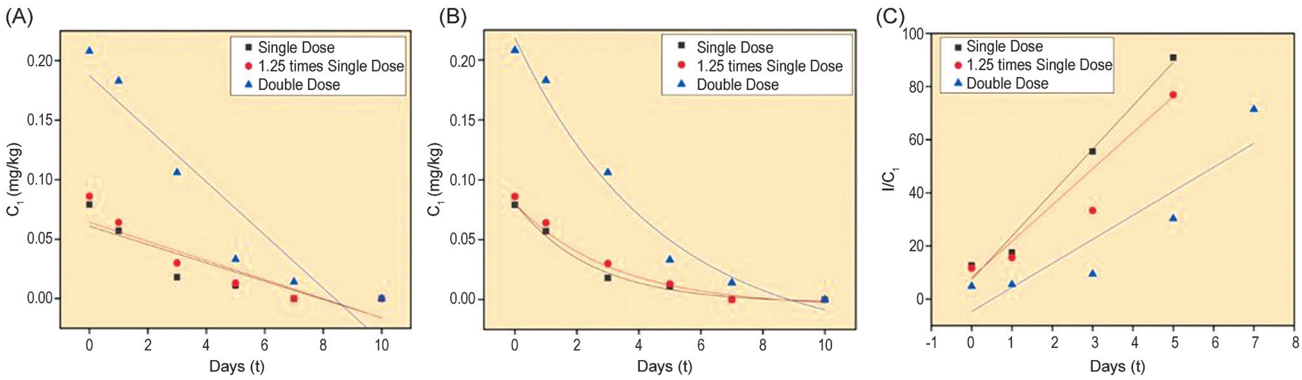

Fig. 2 Fitting chlorantraniliprole dissipation data of okra fruits in (A) zero-order (B) first-order (C) second-order kinetic model.

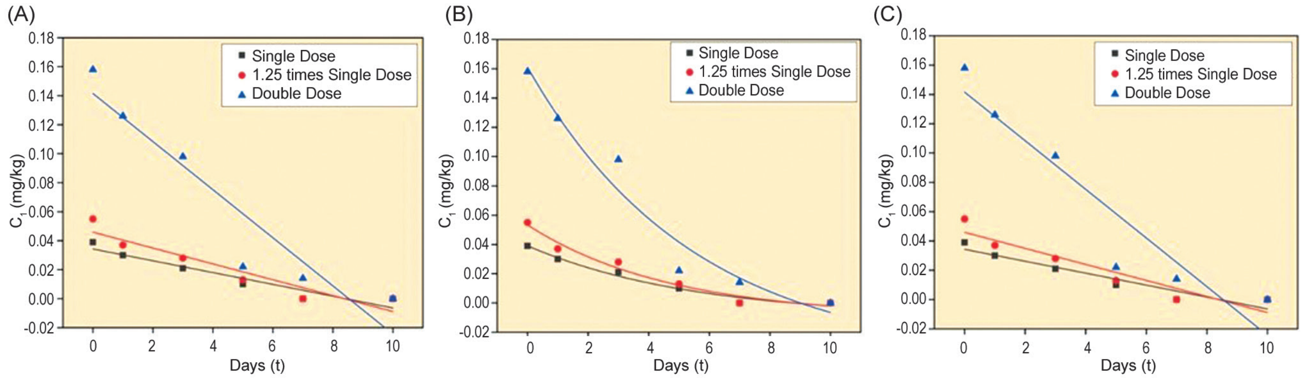

Fig. 3 Fitting lambda-cyhalothrin dissipation data of okra fruits in (A) zero-order (B) first-order (C) second-order kinetic model.

Table 1 Residues of chlorantraniliprole and their dietary risk assessment in okra fruits

Days after the treatment	Treatments											
	28 g a.i./ha (SD)				35 g a.i./ha (1.25 times SD)				56 g a.i./ha (DD)			
	Average residues* ± SD (mg/kg)	% Dissi-pation	EDI	RQ_d	Average residues* ± SD (mg/kg)	% Dissi-pation	EDI	RQ_d	Average residues* ± SD (mg/kg)	% Dissi-pation	EDI	RQ_d
0 (2 h)	0.079 ± 0.001	-	0.0007	0.0000	0.086 ± 0.002	-	0.0008	0.0000	0.208 ± 0.028	-	0.0019	0.0000
1	0.057 ± 0.002	27.84	0.0005	0.0000	0.064 ± 0.001	25.58	0.0006	0.0000	0.183 ± 0.013	12.02	0.0017	0.0000
3	0.018 ± 0.001	77.22	0.0001	0.0000	0.030 ± 0.001	65.11	0.0002	0.0000	0.106 ± 0.007	49.04	0.0009	0.0000
5	0.011 ± 0.002	86.08	0.0001	0.0000	0.013 ± 0.002	84.88	0.0001	0.0000	0.033 ± 0.002	84.13	0.0003	0.0000
7	<LOQ	-	-	-	<LOQ	-	-	-	0.014 ± 0.002	93.27	0.0001	0.0000
10	<LOQ	-	-	-	<LOQ	-	-	-	<LOQ	-	-	-
Half life	1.40				1.97				3.09			
PHI	3.21				3.28				5.86			

	Unacceptable risk (RQ_d > 1)		Moderate risk (RQ_d = 0.1 – 1)		Low risk (RQ_d = 0.01 – 0.1)		Negligible risk (RQ_d < 0.01)

LOQ, 0.01 mg/kg; LOD, 0.005 mg/kg; *, Average residues of three replicates; SD, Standard deviation; EDI, Estimated daily intake; RQ_d, Risk quotient (Human and soil health); LOQ, Limit of quantification; PHI, Pre-harvest interval; SD, Single dose, DD, Double dose.

Table 2 Residues of lambda-cyhalothrin and their dietary risk assessment in okra fruits

Days after the treatment	Treatments											
	28 g a.i./ha (SD)				35 g a.i./ha (1.25 times SD)				56 g a.i./ha (DD)			
	Average residues* ± SD (mg/kg)	% Dissi-pation	EDI	RQ_d	Average residues* ± SD (mg/kg)	% Dissi-pation	EDI	RQ_d	Average residues* ± SD (mg/kg)	% Dissi-pation	EDI	RQ_d
0 (2h)	0.039 ± 0.003	-	0.0003	0.0021	0.055 ± 0.005	-	0.0005	0.0036	0.158 ± 0.012	-	0.0014	0.0101
1	0.030 ± 0.004	23.08	0.0002	0.0014	0.037 ± 0.002	32.72	0.0003	0.0025	0.126 ± 0.010	20.25	0.0011	0.0080
3	0.021 ± 0.001	46.16	0.0001	0.0007	0.030 ± 0.001	45.45	0.0002	0.0014	0.098 ± 0.004	37.97	0.0009	0.0065
5	0.010 ± 0.002	74.35	0.0000	0.0000	0.011 ± 0.002	80.02	0.0001	0.0007	0.022 ± 0.002	86.08	0.0002	0.0014
7	<LOQ	-	-	-	<LOQ	-	-	-	0.014 ± 0.002	91.14	0.0001	0.0007
10	<LOQ	-	-	-	<LOQ	-	-	-	<LOQ	-	-	-
Half life	3.36				3.43				4.36			
PHI	4.47				4.62				5.14			

	Unacceptable risk (RQ_d > 1)		Moderate risk (RQ_d = 0.1 – 1)		Low risk (RQ_d = 0.01 – 0.1)		Negligible risk (RQ_d < 0.01)

LOQ, 0.01 mg/kg; LOD, 0.005 mg/kg; *, Average residues of three replicates; SD, Standard deviation; EDI, Estimated daily intake; RQ_d, Risk quotient (Human and soil health); LOQ, Limit of quantification; PHI, Pre-harvest interval; SD, Single dose, DD, Double dose.

indicating very low dietary exposure. Both investigations consistently demonstrated negligible dietary risk and safe pre-harvest intervals (PHIs). These variations in current findings might be due to different sample matrices, climatic conditions, regions, and different doses of CAP and LC. The PHI values were determined with reference to the maximum residue limits (MRLs) established by FSSAI (2011) for okra, which were 0.3 mg/kg for CAP and LC. The values of PHI suggested that for both the insecticides, the safe waiting period before consumption of okra fruits is between 3–6 days (Table 1–2). The results were in line with Malhat *et al.* (2012) who also suggested that the safe waiting period for harvesting of tomato fruits is eight days after the application of CAP (MRL of 0.6 mg/kg). The waiting period for harvesting of *Aster scaber* is 7 DAA of CAP 5% WG suggested by Yang and Choi (2024). Mohapatra *et al.* (2021) reported that the PHI for LC on pomegranate was 40 days for SD and 54 days for DD after the application of LC 5% EC. The PHI values for lambda-cyhalothrin (4.47–5.14 days) observed in the present study were comparable to those reported in broccoli by Sharma *et al.* (2025), where PHI ranged around 5–7 days. The slightly longer PHI in broccoli may be attributed to its compact curd structure and waxy leaf surface, which can enhance pesticide retention and slow residue dissipation. In contrast, the relatively smooth and exposed surface morphology of okra fruits may facilitate faster degradation and dissipation. Despite minor crop-specific variations, both studies confirmed first-order dissipation kinetics and short waiting periods (<7 days), reinforcing the safe use of CAP and LC under recommended agricultural practices. For CAP, the first-order model exhibited R^2 values ranging from 0.968–0.986 at three different doses, which were higher than those for zero-order (0.728–0.863) and second-order (0.780–0.973) models. Similarly, LC followed first-order kinetics with R^2 values between 0.932 and 0.967, compared to zero-order (0.862–0.890) and second-order (0.844–0.849) models. The comparatively high R^2 values first-order model confirmed that the dissipation of both insecticides is concentration-dependent under field conditions. The dissipation of CAP and LC in soil followed first order kinetics as confirmed by semi-logarithmic plot. The regression equation for CAP at SD, 1.25 SD and DD is y = -0.180x + 1.892, y = -0.165x + 1.954, and y = -0.027x + 2.41, respectively. Similarly, for LC, the regression equations at corresponding doses were y = -0.198x + 1.604, y = -0.159x + 1.734, and y = -0.054x + 2.270. The negative slope values of the regression lines indicated a continuous decline in residue concentration over time, confirming first-order dissipation behaviour of both insecticides under field conditions.

Risk evaluation: The risk quotient (RQ) was used to assess potential harm to human beings and earthworms from

Table 3 Residues of chlorantraniliprole and lambda-cyhalothrin in soil under the okra crop

Days after the treatment	Treatments								
	28 g a.i./ha (SD)			35 g a.i./ha (1.25 times SD)			56 g a.i./ha (DD)		
	Average residues* ± SD (mg/kg)	% Dissipation	RQ_s for earthworms	Average residues* ± SD (mg/kg)	% Dissipation	RQ_s for earthworms	Average residues* ± SD (mg/kg)	% Dissipation	RQ_s for earthworms
				Chlorantraniliprole					
0 (2 h)	<LOQ	-	-	0.014 ± 0.015	-	0.019	0.033 ± 0.018	-	0.044
1	<LOQ	-	-	<LOQ	-	-	0.022 ± 0.012	33.54	0.029
3	<LOQ	-	-	<LOQ	-	-	<LOQ	-	-
5	<LOQ	-	-	<LOQ	-	-	<LOQ	-	-
				Lambda-cyhalothrin					
0 (2 h)	0.010 ± 0.017	-	0.020	0.011 ± 0.009	-	0.022	0.028 ± 0.014	-	0.056
1	<LOQ	-	-	<LOQ	-	-	0.013 ± 0.011	53.71	0.026
3	<LOQ	-	-	<LOQ	-	-	<LOQ	-	-
5	<LOQ	-	-	<LOQ	-	-	<LOQ	-	-

	Unacceptable risk (RQ_s>1)		Moderate risk (RQ_s = 0.1 – 1)		Low risk (RQ_s = 0.01 – 0.1)		Negligible risk (RQ_s<0.01)

LOQ, 0.01 mg/kg; LOD, 0.005 mg/kg; *, Average residues of three replicates; SD, Standard deviation; EDI, Estimated daily intake; RQ_s, Risk quotient (earthworm); LOQ, Limit of quantification; PHI, Pre-harvest interval; SD, Single dose, DD, Double dose.

CAP and LC residues in okra fruits and soil under the crop. CAP imposed negligible risk i.e. RQ_d<0.01 at all the three doses (Table 1) and LC imposed low risk (RQ_d = 0.01–0.1) initially at DD, and showed negligible risk (RQ_d< 0.01) for rest of the days at all three doses (Table 2), indicating no risk to human health from okra fruits. Our dietary risk findings are in line with Kansara *et al.* (2021) who reported that CAP and LC at recommended dose posed negligible risk to the consumers.

Residues of chlorantraniliprole and lambda-cyhalothrin in soil were either below LOQ or present at very low levels across all treatments (Table 3). CAP was mostly undetectable at the SD, while low initial residues at higher doses dissipated below LOQ within three days. Similarly, LC showed low initial deposits, which declined rapidly and became undetectable within three days in most cases. Prominently, all calculated RQ_s values for CAP and LC were below 0.1, indicating negligible risk to earthworms in the soil under the crop which are in accordance to Zuo *et al.* (2024) who reported that the toxicity of various pesticides in vegetable soils, and found that the CAP poses negligible risk to the earthworms and chlorpyriphos poses threat to the earthworms.

The present study demonstrated the dissipation kinetics and risk assessment of CAP and LC applied as a ready-mix formulation in okra fruits and soil. Residue analysis using a validated QuEChERS-GC-MS/MS method confirmed reliable detection (LOQ @0.01 mg/kg). Both insecticides followed first-order dissipation kinetics, with CAP exhibiting short half-lives (1.40–3.09 days) than LC (3.36–4.36 days). Residues declined below the prescribed MRL within 3–6 days, establishing a safe PHI. Dietary risk assessment indicated negligible consumer risk (RQ<0.01) for CAP and minimal risk for LC, even at higher doses. Soil risk evaluation further demonstrated insignificant impact on earthworms. Overall, the findings supported the safe and sustainable use of this formulation in okra cultivation when applied at recommended doses, ensuring effective pest control with minimal environmental and health concerns.

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